RI 9308 REPORT OF INVESTIGATIONS/1990

Laboratory Evaluation of Cable Bolt Supports

(In Two Parts)

1. Evaluation of Supports Using Conventional Cables

By J. M. Goris

1910 ★ 80 YEARS ★ 1990

BUREAU OF MINES

UNITED STATES DEPARTMENT OF THE INTERIOR

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Report of Investigations 9308

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm^3	cubic centimeter	in/min	inch per minute
°F	degree Fahrenheit	lb	pound (mass)
ft	foot	lbf	pound (force)
h	hour	lbf/min	pound (force) per minute
in	inch	lbf/s	pound (force) per second
in^2	square inch	min	minute
in^3	cubic inch	pct	percent
in/ft	inch per foot	psi	pound per square inch
in/in	inch per inch	s	second

LABORATORY EVALUATION OF CABLE BOLT SUPPORTS

(In Two Parts)

1. Evaluation of Supports Using Conventional Cables

By J. M. Goris[1]

ABSTRACT

The U.S. Bureau of Mines is conducting research on cable bolt ground supports to assess their material and support properties, to provide design criteria for using cable bolt supports as roof control systems under various types of underground mining conditions, and to provide a mathematical model of cable bolt support systems. Part 1 describes laboratory studies of the support properties of cable bolts made of conventional steel cables and provides recommendations on such topics as the use of thick grouts, selection of breather tubes, and reduction of water bleeding in cement-based grouts. The studies evaluated both single and double cables; effects of different embedment lengths, water-cement ratios, and grout curing temperatures on support strength; effects of use or nonuse of breather tubes; pumpability and water-bleeding properties of grouts; and the strength properties of sand-cement grouts. Part 2 will cover the strength characteristics of birdcage cable bolt supports, epoxy-coated cables, and cables with steel buttons attached.

[1]Mining engineer, Spokane Research Center, U.S. Bureau of Mines, Spokane, WA.

INTRODUCTION

Cable bolts were introduced to the mining industry around 1970 as a means of reinforcing ground prior to mining. In the United States, cable bolts were first used in 1977 by the Homestake Mining Co. at its underground gold mine in Lead, SD. To date, four other mines in the United States either are using or have used cable bolt supports.

Cable bolts consist of one or more steel cables grouted into a drill hole in the rock (fig. 1). These supports vary in length, but 60-ft lengths or greater are common. The cables are made from high-strength steel having an ultimate strength of approximately 58,000 lbf and a modulus of elasticity of approximately 29.5×10^6 psi. They usually have a diameter of 0.6 to 0.625 in and consist of seven wires (fig. 2).

Cable bolts can be installed at any angle in the rock. When installed in an uphole, which is a hole drilled at an angle above the horizontal, the following steps are taken:

1. The cable and a plastic breather tube are inserted into the hole. The breather tube allows the air being displaced by the grout to escape. Also, when grout runs out of the tube, it indicates to the cable bolt crew that the hole is filled.
2. Water is sent through the breather tube to flush the hole.
3. A plastic grout tube is pushed approximately 3 ft into the hole.
4. The bottom 12 in of the hole is plugged.
5. The hole is then filled with a cement-based grout through the grout tube. The grout consists of portland cement and water at ratios between 0.3 and 0.45 parts of water to 1 part of cement by weight.
6. After the hole has been filled, the ends of the two tubes are folded over and tied off to prevent the grout from draining. These tubes then become a permanent part of the support system.

There are exceptions to this process of installing cables in upholes. Recently, several mines in other countries began using a thick grout (water-cement ratio equal to 0.3) that is placed in the drill hole without the hole being plugged. The holes are filled from the top of the hole down, and therefore do not require a breather tube.

On downholes, the breather tube is not required, and the grout tube does not remain in the hole, but is retrieved as the hole fills with grout.

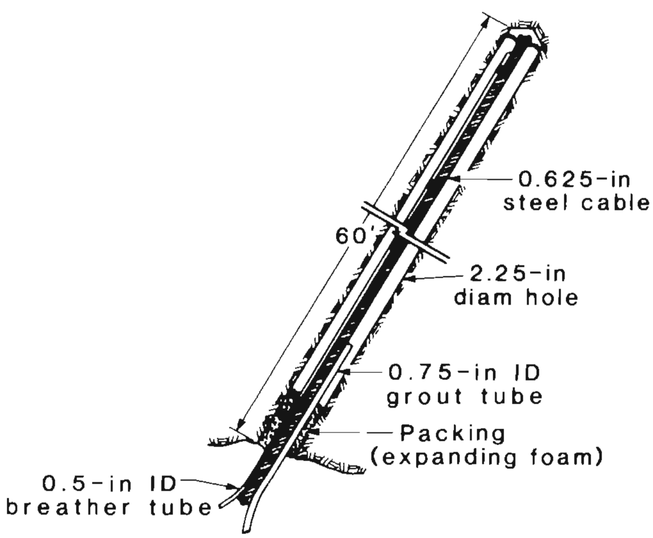

Figure 1.–Cutaway view of typical cable bolt support.

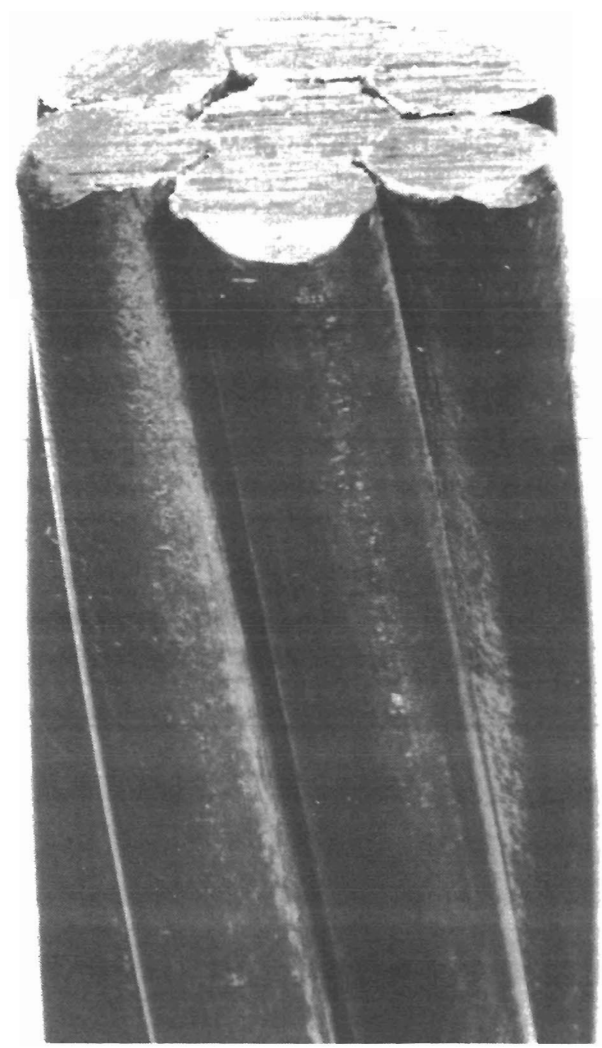

Figure 2.–Seven-wire steel cable.

The steel cable used for cable bolt supports is very flexible and can be laid into a 4-ft-diam coil. This flexibility is one of the primary advantages of cable bolt supports because long supports (60 ft or greater) can be installed in a drift that has less than 8 ft of headroom. Consequently, cable bolt supports are used to reinforce rock before mining, thereby providing rock support around an opening after a portion of the rock has been blasted.

For a cable bolt support system to be effective, load from the rock must be transferred to the cable through the grout. Therefore, the capacity of the system depends on the strength of the grout, the cable, and the interfaces between the grout and cable and between the rock and grout. Failure may occur in one or more of the following modes:

1. Failure at the grout-cable interface.
2. Failure at the rock-grout interface.
3. Failure of the cable.
4. Failure of the rock around the cable bolt.

Of these, failure at the grout-cable interface appears to be the most common, and it is in this area that most research has been concentrated to date.

Cable bolts work well in fractured ground because the entire length of the cable is bonded to the rock with grout. Also, cable bolt support patterns can be designed to respond to various types of ground movement. In highly stressed rock, single cables in each hole allow large amounts of rock deformation to occur, thereby redistributing load to the pillars. Double cables, on the other hand, have very high load-carrying capacities at low displacements, thereby allowing less displacement to take place for a given load.

Since cable bolts were introduced in the early 1970's, considerable research has been conducted in laboratories and at mine sites to understand their behavior under uniaxial loading conditions. The laboratory phase of the U.S. Bureau of Mines cable bolt evaluation project was initiated to study the behavior of cable bolts under uniaxial loads so that the effects of various cable bolt components, such as grout and breather tubes, could be identified. Other objectives were to compare the behavior of various types of cables and grouts and to provide meaningful data for numerical analyses. Part 1 of this report covers laboratory research conducted on cable bolt samples containing conventional 0.625-in-diam steel cables, cement-based grouts, and 0.25- to 0.5-in-diam breather tubes. Pull tests were conducted to determine how cable bolts react under uniaxial loads and how they fail when ultimate shear stresses are exceeded. Such data are essential for the development of numerical models for analyzing rock mass behavior when the rock is supported with cable bolts.

ACKNOWLEDGMENTS

Special thanks go to Ray Anderson, Tom Brady, and Lewis Martin of the Spokane Research Center, who were instrumental in the development of testing procedures, the preparation and testing of test samples, and the evaluation of laboratory test data. Special acknowledgment is also given to the management and technical personnel at the Homestake Mine, Lead, SD, for their guidance with this project.

TEST PROGRAM

Because each cable bolt support can contain single or double cables as well as a breather tube, the test program was designed around pull tests on a variety of samples containing these components. The first series of samples containing a single cable, a neat cement grout with a water-cement ratio of 0.45, and no chemical additives was selected as a standard. Then one variable in the system, such as the use of a breather tube, was changed, and a second series of samples was made and tested and the results compared with results obtained for series 1. If significant changes in test data occurred, they could be attributed to that one variable. Each component of the cable bolt system, that is, cable, grout, and grout tube, was studied to determine what influence that component might have on the behavior of the support system. To control the quality of the samples, the physical condition of the cables and tubes was monitored closely, and compressive and tensile strengths as well as flow properties were determined for the grout used in each test series. Summaries of the test series are shown in table 1.

Various combinations of cables and tubes were embedded in grout columns inside the pull-test apparatus, cured for a specific period, and then tested to determine the load-displacement characteristics of the samples. From such data, engineers determined maximum load, shear stress, elastic zones, and residual load-carrying characteristics for each sample.

Table 1.–Test series conducted during laboratory evaluation of supports with conventional cables

Test series	Variable being studied	Description of test samples
1	Cable	Single cable, but no breather tube.
2A	Cable embedment length	Single cable, no breather tube, and cables embedded 3 to 20 in.
2B	.. do	Single cable, no breather tube, and cables embedded 22 to 30 in.
3A	Breather tube filled with grout	Single cable, 1/4-, 3/8-, and 1/2-in breather tubes filled with grout.
3B	.. do	Do.
3C	Breather tube not filled with grout	Single cable, 1/2-in breather tube not filled with grout.
4	Water-cement ratios	Single cable, but no breather tube.
5	High temperatures	Same as series 1, except samples cured at 127° F.
6A	Sand-cement grout	Single cable with sand-cement grout, but no additive.
6B	.. do	Same as 6A, except with water-reducing admixture at 0.25 lb per 100 lb cement.
6C	.. do	Same as 6A, except with water-reducing admixture at 0.45 lb per 100 lb cement.
7	Cable	Two cables, but no breather tube.
8	.. do	Two cables with 1/2-in breather tube filled with grout.

PULL-TEST APPARATUS

The pull-test apparatus is shown in figure 3 and consists of two 2.62-in-diam steel pipes through which the cable is run. The portion of the cable embedded in the 12-in (bottom) pipe is the segment actually being tested. There are approximately 4 in of cable extending beyond the end of this pipe. To prevent slippage of the end of the cable embedded in the 20-in (upper) pipe, a 1.75-in-diam by 1.5-in-long barrel-and-wedge steel anchor was attached to the cable and a load of 25,000 lbf applied to set the anchor prior to making the pull-test sample. This apparatus was adopted from one used by Fuller and Cox in Australia (*1*);[2] however, some modifications were made, such as use of the barrel-and-wedge anchor.

The purpose of using the pipe apparatus was to confine both ends of the cable to prevent rotation during testing. Cable rotation causes the cable to unscrew out of the grout column as a threaded rod does. The pipes were inexpensive and provided great flexibility in making, handling, and storing test samples. The major drawback was that the load-displacement curve for the cable bolt sample was not likely to be exactly what support systems experience in a large rock mass because the stress-strain behavior of pipe is different from that of rock. However, the relative behavior of one laboratory test sample to another should approximate the behavior of cable bolts in rock. The type of cable and the sizes and types of breather and grout tubes in the pull tests were selected to duplicate those used in the Carr Fork Mine, Tooele, UT, and the Homestake Mine (*2*).

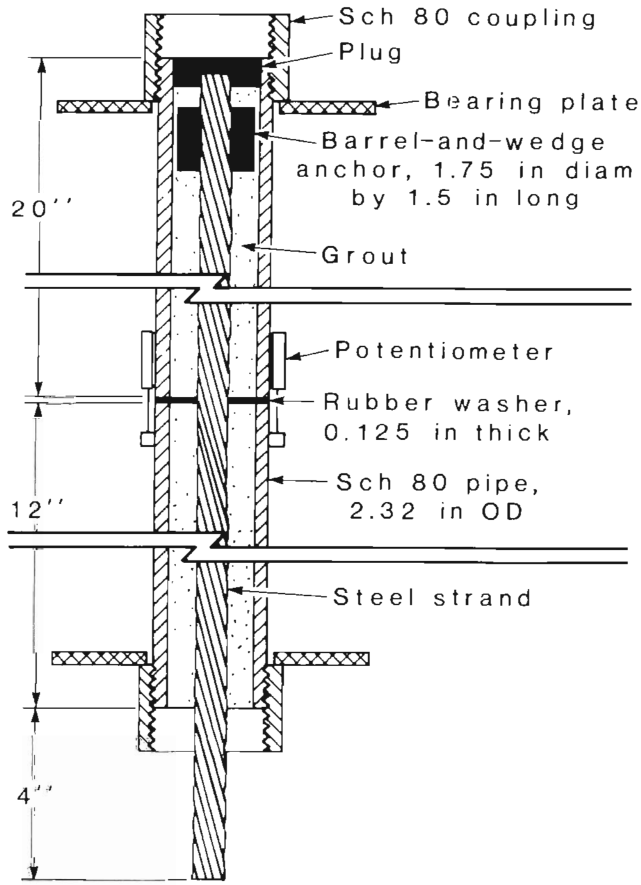

Figure 3.–Pull-test apparatus.

[2]Italic numbers in parentheses refer to items in the list of references at the end of this report.

STRAIN TESTS ON PIPE ASSEMBLY

There was concern that the pipe casings used for pull tests might be overstressed during testing if loads approached 60,000 lbf. Consequently, a 30-in-long pipe containing no grout or cable was instrumented with strain gauges just below a coupling on one end of the pipe (fig. 4). This is the area of highest stress during a pull test because it is the thinnest region of the pipe. The pipe was then placed in the test machine and loaded up to 60,000 lbf, which exceeded the rated tensile strength of a single 0.625-in-diam cable by about 2,000 lbf.

Results from pull tests on the instrumented pipe are shown in figure 5. The four curves shown in figure 5*A* represent the stress-strain behavior of the pipe during loading and unloading. The average of readings of the two inside longitudinal gauges shows the highest value of strain, approximately 0.000973 in/in, or 973 microstrain ($\mu\epsilon$), at a load of 60,000 lbf, whereas the average reading for the outside longitudinal gauges, located at the center of the pipe, shows approximately 900 $\mu\epsilon$. Assuming a Young's modulus of 29.5×10^6 psi for the pipe and an area of 2.25 in^2, the theoretical strain is 904 $\mu\epsilon$. Consequently, the pipe was not being overstrained at a load of 60,000 lbf and was safe to use as part of the pull-test apparatus.

The curve that represents the inside longitudinal gauges in figure 5*A* starts at a value of approximately -35 $\mu\epsilon$, indicating that the threads in this region are in compression. This is the result of using a wrench to tighten the pipe coupling before testing. When the coupling was hand tightened, a reading of approximately -0.9110 $\mu\epsilon$ was obtained. After the pipe was loaded and unloaded, the average reading on these gauges was approximately 2 $\mu\epsilon$.

Figure 5*B* shows the Poisson's ratios for the pipe as the load was increased. This ratio represents lateral contraction of the pipe (indicated by the negative strain values for the outside lateral gauges in figure 5*A*) divided by the axial elongation (indicated by the positive strain values for the outside longitudinal gauges). The average Poisson's ratio for the pipe during the test was approximately 0.27.

PREPARATION OF TEST SAMPLES

Pull-Test Samples

Figure 6 shows pull-test samples being prepared. This was accomplished by inserting the cable into a 20-in-long pipe and holding it there by a No. 11.5 rubber stopper at the bottom of the pipe. The pipe was then filled with grout, and a 1/8-in-thick rubber washer, coated with petroleum jelly to prevent the grout from adhering to the washer, was placed on top. A 12-in-long pipe was then placed on top of the 20-in-long pipe and secured with a sleeve clamp. The top pipe was filled with grout and the top portion of the cable was centered in the pipe by placing a threaded steel cap, having a 3/4-in-diam hole in the center, over the end of the cable and screwing it on the pipe. Grout sedimentation began taking place within minutes of placing the grout; consequently, additional

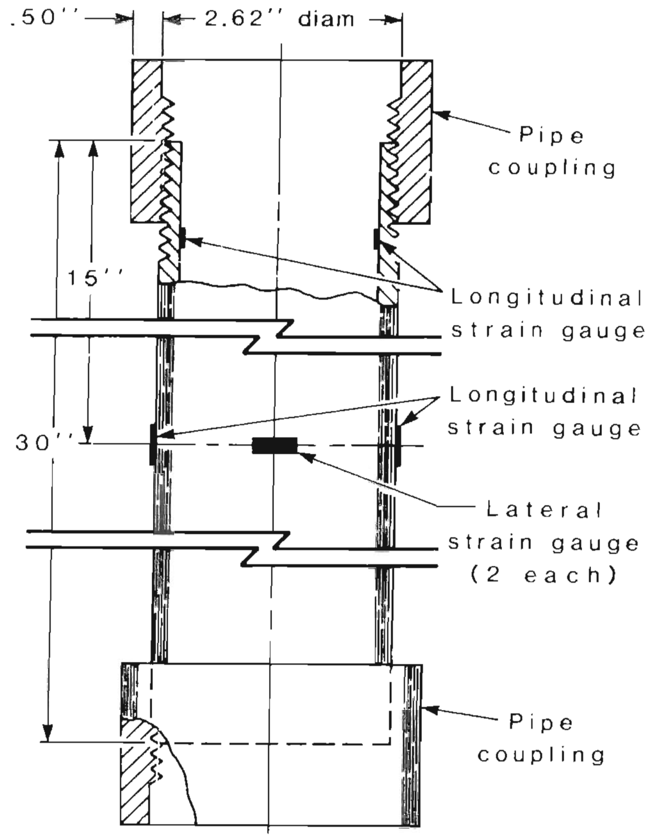

Figure 4.–Pull-test pipe instrumented with strain gauges.

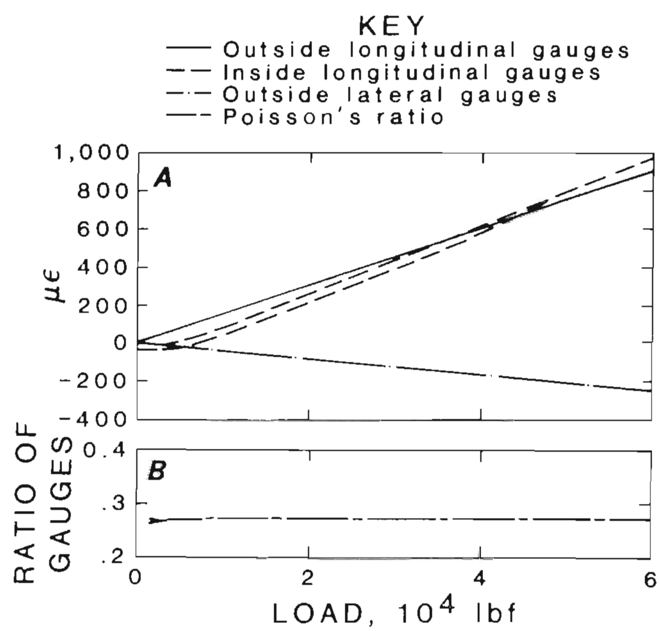

Figure 5.–Test results on instrumented pipe. *A*, Load-strain behavior; *B*, Poisson's ratio.

Figure 6.–Pull-test samples being prepared.

grout was added to the top pipe after about 5 min. However, sedimentation continued for several hours after the grout was placed. Therefore, the final length of cable embedment was determined by measuring the amount of grout settlement and subtracting this value from initial embedment length. The top of each sample was then covered with a plastic bag to reduce water evaporation, and the samples were cured in place for 24 h; they were then placed in a curing room at a temperature of 70° F and 100 pct humidity.

Compression and Tension Samples

Thirty grout samples were prepared, five each for the compression and tension tests to be done at 3, 7, and 28 days of curing. The compression samples were cast in 2-in^3 brass molds under the American Society for Testing and Materials (ASTM) Standard C 109 and stored in a curing room at 70° F and 100 pct humidity for the specified curing period. The tension samples (fig. 7) were cast in brass briquet molds under ASTM Standard C 190 and cured in the same manner as the compression samples.

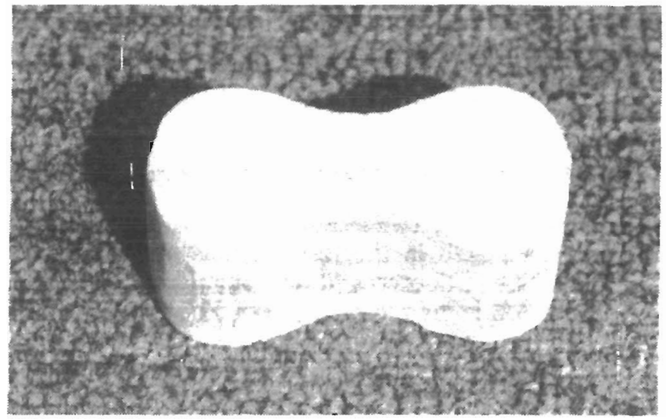

Figure 7.–Grout tension briquet. The cross section is 3 in long by 1 in thick at its narrowest dimension (center).

TEST PROCEDURES

Pull Tests

Pull tests on the cable bolt samples were conducted on a hydraulic test machine with a 400,000 lbf capacity (fig. 8). Each test sample was selected at random from the appropriate group of samples. When the test was in progress, the upper head of the test machine would move away from the lower head, causing the two pipes of the pull-test sample to separate. Because the end of the cable in the larger pipe was secured in place with a barrel-and-wedge anchor, as displacement of the pipes occurred, the end of the cable in the shorter pipe debonded from the grout and shearing took place along the grout-cable interface. The rate of displacement was set at 0.6 in/min, and the amount of force applied varied according to the cable pull-out resistance. Loading was continued until the total displacement was about 6 in.

Figure 8 shows a sample being tested. The important data being collected are uniaxial loads applied to the sample, which forces the cable to slip, and the displacement or degree of slippage taking place. The loads were recorded in the form of an electrical signal from a load cell within the test machine. Displacement was obtained from two potentiometers attached to the pull-test sample (fig. 8) and from a linear variable differential transformer (LVDT) attached to the head of the test machine. The output from the potentiometers and the LVDT, which serve as backups to one another, was approximately the same. There was a third potentiometer attached to the portion of the cable that extends past the end of the shorter pipe. This potentiometer was used to sense when the entire length of the cable embedded in the smaller pipe began to slip, thereby indicating that the bond had broken along the entire length

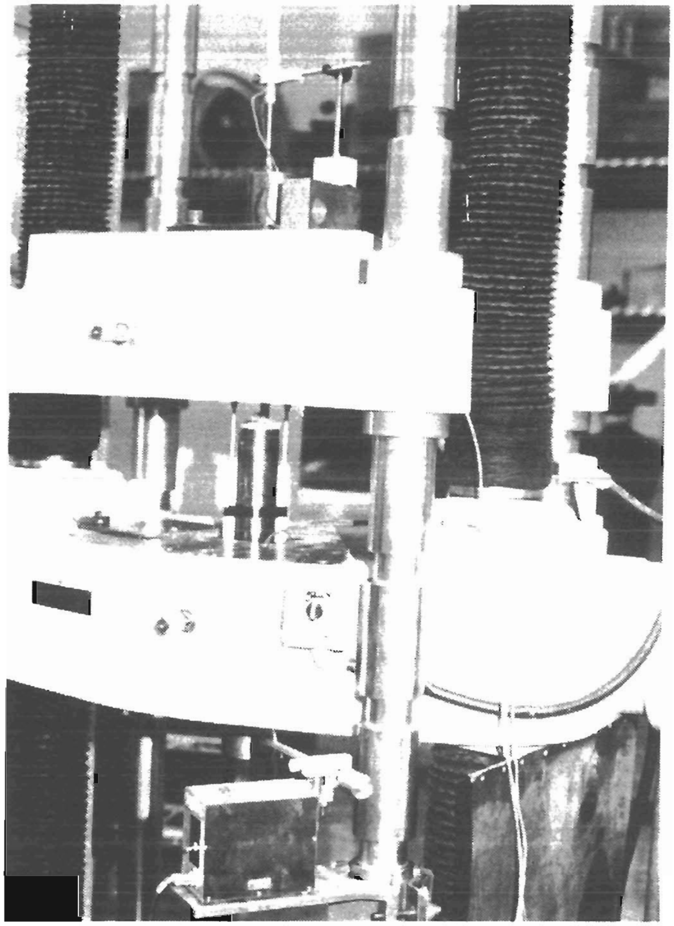

Figure 8.-Hydraulic test machine with pull-test sample.

of this portion of the cable. For every sample tested, shear failure occurred between the cable and the grout. No detectable slippage took place between the grout and pipe interface.

Rotation of the two pipes and the cable in each pull-test sample was monitored visually during the test by etching common reference lines on the bearing plates of the test apparatus and on each pipe, as well as on the cable protruding from the bottom of the sample (fig. 3). Horizontal displacement of these reference lines with respect to one another during the test would indicate rotation.

Physical Property Tests on Grout

Compression tests on grout samples were conducted on a 200,000-lbf capacity, screw-type machine (fig. 9). The molds used in casting the grout cubes were well within the tolerances specified by ASTM Standard C 109; consequently, the faces of the cubes did not have to be modified to ensure parallel surfaces. Head movement on the test machine was set at a rate of 0.10 in/min until the compressive load reached 3,000 lbf, then the rate was reduced to 0.05 in/min for the remainder of the test.

Tension tests on grout samples were conducted on a manually operated testing machine (fig. 10) under ASTM Standard C 190. The load was applied at a constant rate of 600 ± 25 lbf/min.

In addition to compressive and tensile strength properties for the grout, Young's modulus was also determined by making five 3-in-diam by 6-in-long cylindrical grout samples under ASTM Standard C 873. After being cured for 24 days, the samples were instrumented with four 1-in-long paperback strain gauges. The gauges were placed around the center of each cylinder, two in a lateral position opposite one another and two in a longitudinal position opposite one another. The compression tests necessary to determine Young's modulus were conducted on the 28th day of curing on a hydraulic machine with a capacity of 400,000 lbf. Constant loads were applied to the cylinders at a rate of approximately 200 lbf/s. Loading was stopped at intervals of 2,000 lbf and the load held constant while the strain gauges were read. Test data were then reduced and the modulus determined using the following procedures as recommended by ASTM Standard C 469:

$$E = (S2 - S1)/(\epsilon 2 - 0.00005)$$

where E = Young's modulus, psi,

S1 = stress corresponding to 40 pct of the ultimate compressive strength of the sample, psi,

S2 = stress corresponding to a longitudinal strain of 0.05 $\mu\epsilon$, psi,

and ϵ = longitudinal strain produced by stress S2, $\mu\epsilon$.

Flow tests were also conducted on the grout to determine the relative viscosities of the different grouts. The tests were conducted under the U.S. Army Corps of Engineers test CRD-C611-80, "Test Method for Flow of Grout Mixtures (Flow Cone Method)." Figure 11 shows the cone. The grout flow rate is determined by placing 1,725 cm^3 of grout in the cone while covering the outlet on the bottom with a finger. The finger is removed while a stop watch is started simultaneously. The watch is stopped at the first break in the continuous flow of the grout from the discharge tube of the cone. The efflux time is approximately 11 s for water and 15 s for a grout with a water-cement ratio of 0.45.

ANALYSIS OF TEST DATA

The pull tests were expensive and very time consuming; consequently, the number of tests run for each test series was limited to five samples for each curing period, that is, 3, 7, and 28 days. The analysis of the test results, therefore, was very critical because sample populations were

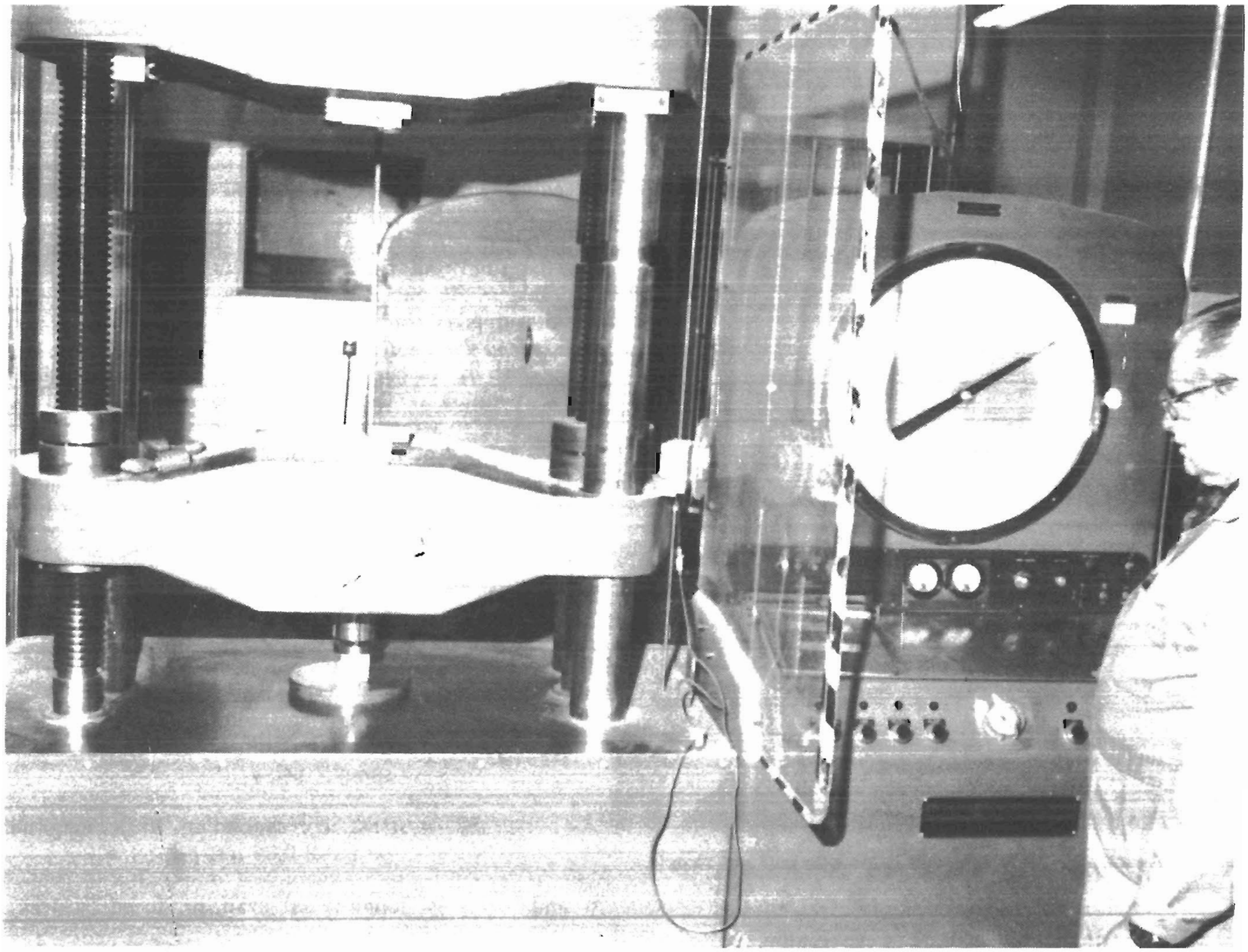

Figure 9.–Screw-type machine used for compression tests on grout samples.

small. The pull-test procedure and the data obtained were first analyzed by observing the performance of each sample as it was tested and identifying and recording inconsistences, such as the center wire of the cable not being pulled from the sample or the threads being stripped from the pipe. If the tests were successful, the data were plotted and then analyzed by evaluating the load-displacement relationship of each sample, that is, maximum loads and stresses. All five load-displacement curves for each test period were averaged using a computer so that the load-displacement trends could be evaluated. Next, the maximum shear stresses and/or maximum loads were analyzed statistically to provide an indication of the similarity of the samples in each series and a guide for comparing the performance of one set of test samples with another.

The statistical methods used in the data analysis were an attempt to answer several important questions. First, were the results from a given series consistent, thereby indicating that the samples were made and tested in a consistent manner? In general, this question was addressed by computing the coefficient of variation of the data set, which is equal to the standard deviation of the data set divided by the mean, which is expressed as a percentage. If the coefficient were $\leq$15 pct for pull tests and $\leq$7 pct for compressive and tensile strength tests, then the data were considered comparable. If the coefficient exceeded these values, the data were then reexamined for possible errors, and, if necessary, the test series was rerun.

Second, given two or more sets of data from different series, did the sets come from the same population or from a different one? To answer this question, the Student's T-test was used to compare two sets of data, and an analysis of variance was used to compare three or more sets of data. The data being analyzed were either maximum shear stresses or maximum loads.

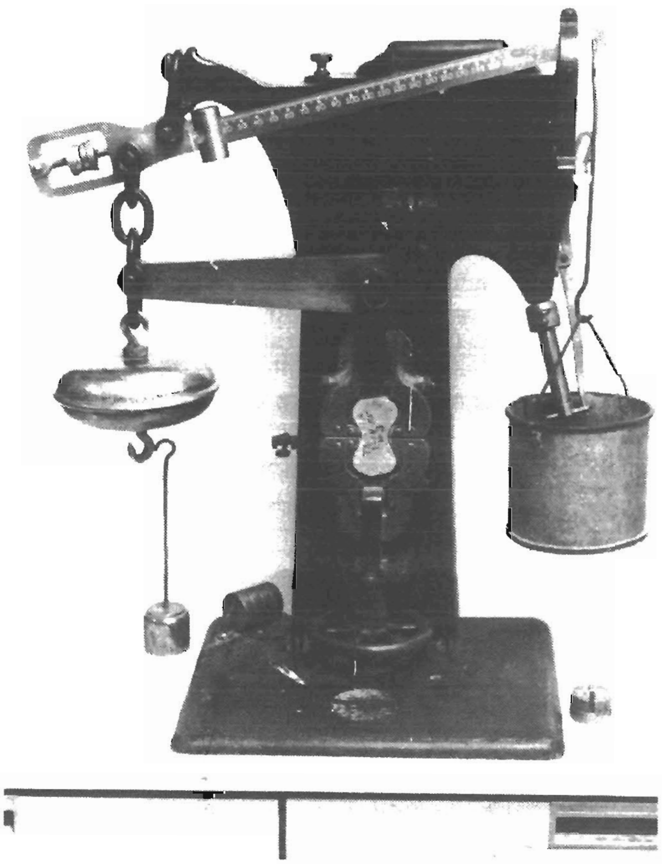

Figure 10.–Manually operated test machine used for tension tests on grout samples.

Figure 11.–Flow cone used for conducting flow tests on grout.

The T-test is applicable to several types of hypotheses; however, the one used for analyzing pull-test data, as well as compression and tension test data, assumed that mean shear stresses, or mean maximum loads, from two sets of data came from identical populations. That is, it was assumed that any changes made to the standard single cable samples would not influence mean shear stress and/or mean maximum load. It was further assumed that the test results from the two sets of data being compared were representative of the particular sample and that the data sets had normal distributions. A significance level of 5 pct was selected; this meant that there was a 5 pct probability of falsely rejecting the hypothesis.

The T-value was calculated using mean shear stresses or mean maximum loads, standard deviations, and sample sizes. This value was then compared to the standard coefficient for a normal distribution (Z-value), which was based on the degrees of freedom of the data sets and a significance level of 95 pct. If $-Z < T > +Z$, then the hypothesis was accepted, and the two sets of data were from the same population. This implied that whatever changes were made from one test series to another did not influence the behavior of the pull-test sample.

The analysis of variance test compares mean shear stresses or mean maximum loads of three or more sets of data. For this test, the hypothesis was that all sets of data were from the same population. It was also assumed that test results were representative of the particular sample configurations, that the results had normal distributions, and that all populations had the same variance.

The important statistic derived from the analysis of variance is the F-ratio, which is an indication of the degree of variation between data sets. If the F-ratio is large, then variation between sets of data is much greater than variation resulting from random error, and the hypothesis is rejected; that is, the data sets are not from the same population and changes made to the samples do influence their behavior. To determine whether the F-ratio was large, it was compared with a critical value selected from a F-table (*3*). This critical value is based on the degree of freedom of the populations and the level of significance, which was 95 pct.

TEST RESULTS

The shear stress developed along the grout-cable interface for a given load during a pull test was calculated by dividing that load by the contact area between the cable and the grout. The circumference of a 0.625-in-diam cable is 2.62 in, as calculated by the equation

$$C = N \times 3.14 \times D \times [\sin(360/2N)/\sin(360/2N) + 1] \times (0.5 + 1/N),$$

where C = circumference of the cable, in,

N = number of outer wires of the cable,

and D = diameter of the cable, in (*4*).

For the cables used in this laboratory study, $N = 6$ and $D = 0.625$ in; therefore, $C = 2.62$ in. The contact area is therefore 2.62 in multiplied by the length of embedded cable in the pipe.

STANDARD TEST SAMPLES

Test series 1 (table 1) represents the standard to which all other results were compared. The pull-test samples contained a cement grout with a water-cement ratio of 0.45, a single 0.625-in-diam cable, but no breather tube or chemical additives. Results from the pull tests and strength tests on the grout are shown in table 2.

Table 2.–Summary of 28-day test results for all test series

Test series and measurement	Pull tests		Grout tests		
	Max. load, lbf	Max. shear stress, psi	Compressive stress, psi	Tensile stress, psi	Flow time, s
1	19,820	668	6,940	588	14.0
2A, embedment, in:					
8	14,700	765			
10	18,960	776			
12	19,300	661			
14	21,600	630	7,291	454	14.8
16	23,120	592			
18	25,360	576			
20	28,840	590			
2B, embedment, in:					
22	31,020	538			
24	36,320	578			
26	37,920	556	7,175	458	15.1
28	41,360	563			
30	43,040	547			
3A, tube diameter, in:					
1/4	19,650	655			
3/8	18,982	650	7,109	523	14.0
1/2	19,200	640			
3B, tube diameter, in:					
1/4	19,888	676			
3/8	20,050	691	7,265	476	14.5
1/2	19,934	682			
3C, tube diameter, in 1/2	17,660	593	7,258	572	14.7
4 water-cement ratio:					
0.3	36,820	1,192	9,844	585	([1])
0.35	32,080	1,035	8,175	540	([1])
0.4	26,100	873	7,580	517	([1])
[2]0.45	19,820	668	6,940	588	[2]14.0
5	22,900	791	([3])	([3])	31.6
6A	27,920	900	7,600	721	([1])
6B	27,592	896	7,490	814	39.6
6C	27,195	865	7,605	759	37.0
7	[4]41,080	838	6,748	610	13.8
8	[4]43,058	881	7,103	583	16.0

[1]Grout was too thick to conduct test.
[2]Same as test series 1.
[3]Samples could not be tested due to shrinkage cracks.
[4]Samples contained two cables.

The pull-test samples in test series 1 were also the least complicated and provided a basic understanding of the failure mechanics of such supports under uniaxial loads. The length of embedment for each cable tested was 12 in; however, sedimentation took place in the grout as it cured. Consequently, the average length of embedment for these samples was actually 11.3 in.

For each pull-test, a load-versus-displacement curve was obtained. Figure 12 shows the average curves for the 3-, 7-, and 28-day tests for test series 1. As the grout cured and became stronger and less ductile, the pull-test samples gained greater maximum and residual load-carrying capacity. This characteristic was true for all samples tested; however, the shapes of the curves and relative increase in maximum strength and residual load-carrying capacity varied from one test series to the next.

Displacement in this figure represents the separation of the two pipes as the testing apparatus was loaded (fig. 8). Because there were two different size pipes in the test apparatus, the end of the cable in the shorter pipe offered the least resistance to pullout and, consequently, pulled out of the grout as the load applied to the system was increased. This process simulated a small mass of rock falling from the back and pulling away from a support cable.

In the curve representing the 7-day tests, section A-B represents initial loading of the samples. As the load was increased, the bond between the cable and grout began to break, and the segment of the cable closest to the junction of the two pipes began to elongate. The slope of A-B is approximately 10,000 lbf per 0.12 in of displacement. This displacement cannot be attributed to elongation of the cable alone, but is the sum of elongation of the embedded cable, elongation of the unembedded 0.125-in segment of cable between the two pipes (fig. 3), elongation of the pipe

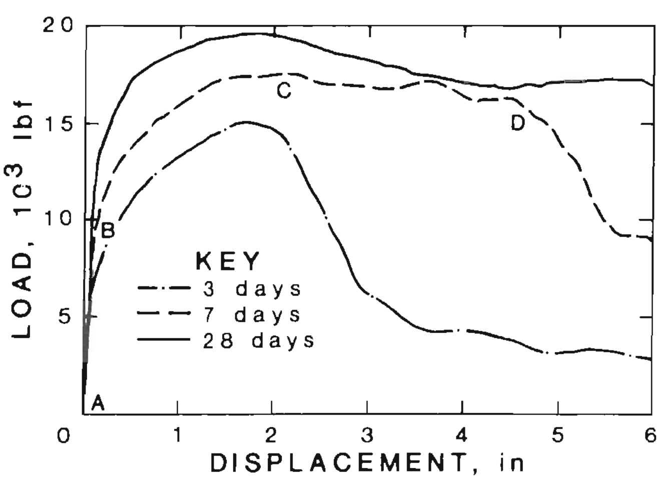

Figure 12.–Averaged 7-, 14-, and 28-day load-displacement curves, test series 1. Letters indicate sections of the 7-day curve discussed in text.

and grout column, and any initial movement in the testing system when loading began. An accurate determination of elongation of the cable was made by instrumenting a single cable with six SR4 strain gauges in the region embedded in the 12-in pipe to determine the strain at three locations along the cable. Figure 13 shows the location of the gauges. Figure 14 shows the actual pull-test data for the gauges plotted along with theoretical values for strain of the cable at the location of the upper gauges.

The theoretical strain at a given point on an embedded cable can be expressed by the equation

$$\epsilon = (P/AE)\ (1\text{-}Y/L)^2$$

where ϵ = strain,

P = load, lbf,

A = cross-sectional area of the cable, in^2,

E = Young's modulus of the cable, psi,

Y = a given point along the cable, in,

and L = length of embedded cable, in (5).

Therefore, given a load of 7,500 lbf, a Young's modulus of 29.5×10^6 psi, a cable area of 0.22 in^2, and an embedment length of 12 in, the strain at Y = 0.75 in (location of upper gauges 1 and 2 in figure 14) should be

$$\epsilon = [7{,}500/(0.22)\ (29.5 \times 10^6)]\ [1 - (0.75/12)]^2$$

$$= 1{,}020\ \mu\epsilon.$$

This value is quite close to the laboratory result of approximately 940 $\mu\epsilon$ for the average of the upper gauges (fig. 14).

The total elongation of the cable for a given length of embedment and at a given load can be approximated by the equation

$$\delta = 0.125P/AE + \int_0^{L1} \epsilon\ dy + \int_0^{L2} \epsilon\ dy,$$

where δ = total elongation, in,

L1 and L2 = lengths of embedded cable in each pipe, in,

and 0.125P/AE = elongation of the unembedded segment of cable between the pipes.

Therefore, substituting for ϵ and simplifying,

$$\delta = P/AE\ [0.125 + \int_0^{L1}(1\text{-}Y/12)^2\ dy + \int_0^{L2}(1\text{-}Y/12)^2\ dy].$$

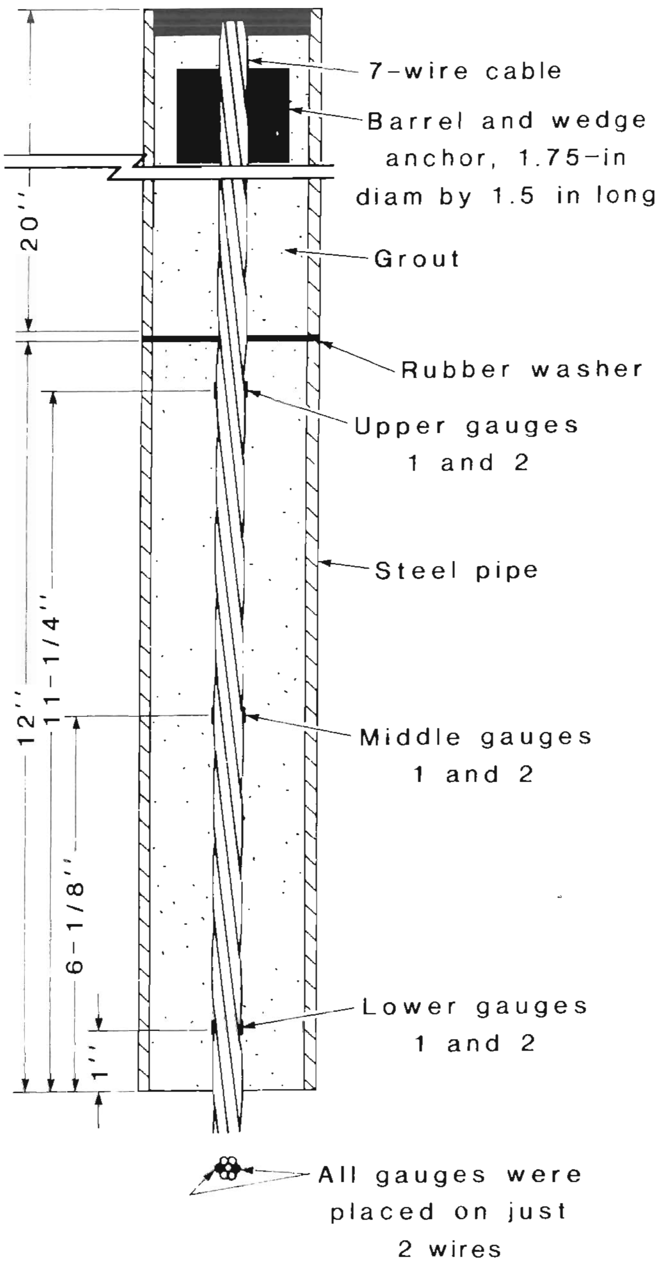

Figure 13.-Cable bolt pull-test sample with strain gauges.

Given a load of 10,000 lbf, a cross-sectional area for the cable of 0.22 in^2, a Young's modulus for the cable of 29.5×10^6 psi, and a length of cable embedment of 12 in (it is assumed that 12 in of the cable in the 20-in-long pipe will also elongate, therefore, L1 = L2 = 12 in), then $\delta = (10{,}000)/(0.22)\ (29.5 \times 10^6)\ [0.125 + 4.000 + 4.000] = 0.013$ in.

The remaining question is, how can one account for the remaining 0.107 in of displacement in the system since the displacement in figure 12 was 0.12 in at a load of 10,000 lbf? Part of the displacement came from the test assembly

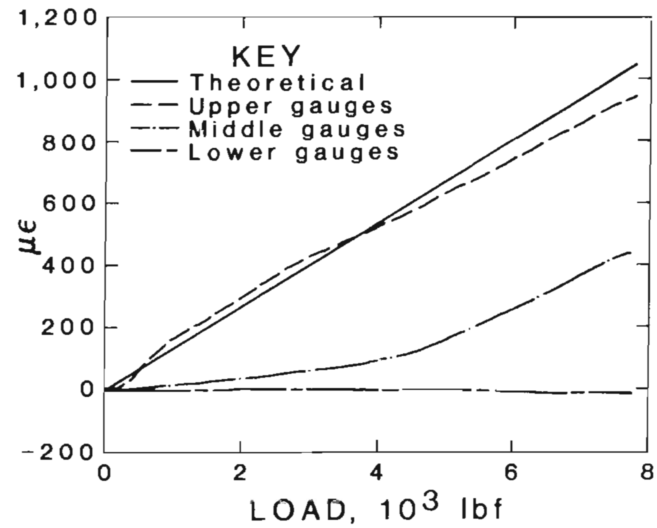

Figure 14.-Test results for pull-test sample with strain gauges.

when uniaxial loads were applied; additional elongation most likely came from microshrinkage cracks that developed perpendicular to the cable as the grout cured. Figure 15 shows these cracks in a cross section of a pull-test sample. As the pull-test samples were loaded, these microcracks began to open and allowed elongation of the grouted column to take place along their vertical axes.

Referring once again to figure 12, as the load was increased between points A and B, the bond between the grout and cable was broken, first at the junction of the pipes and then propagating along the length of the cable in both the 12- and 20-in pipes. At point B, the bond along the entire length of the cable embedded in the 12-in pipe was broken and the 12-in section of pipe and grout began to slip along the surface of the cable. This is analogous to a small mass of rock beginning to fall from the back in a mine opening. Also, the bond was broken along the first 12 in of cable in the 20-in pipe; however, because there was an additional 8-in length of embedded cable and additional resistance to pullout provided by the steel anchor attached to the cable, this section of the cable did not slip. This condition was verified with each sample tested by inspecting the bottom of the 20-in pipe to see if the cable had moved.

As loading continued past point B, the cable in the 12-in pipe continued to slip along the grout-cable interface. However, because neither the cable nor the grout column could rotate, the cable began to shear the ridges of grout between individual wires. The ridges are similar to riflings in the barrel of a rifle and can be seen in the cutaway sample in figure 15. As loading continued, the grout particles sheared from these ridges became wedged between individual wires of the cable, thereby increasing the resistance to movement.

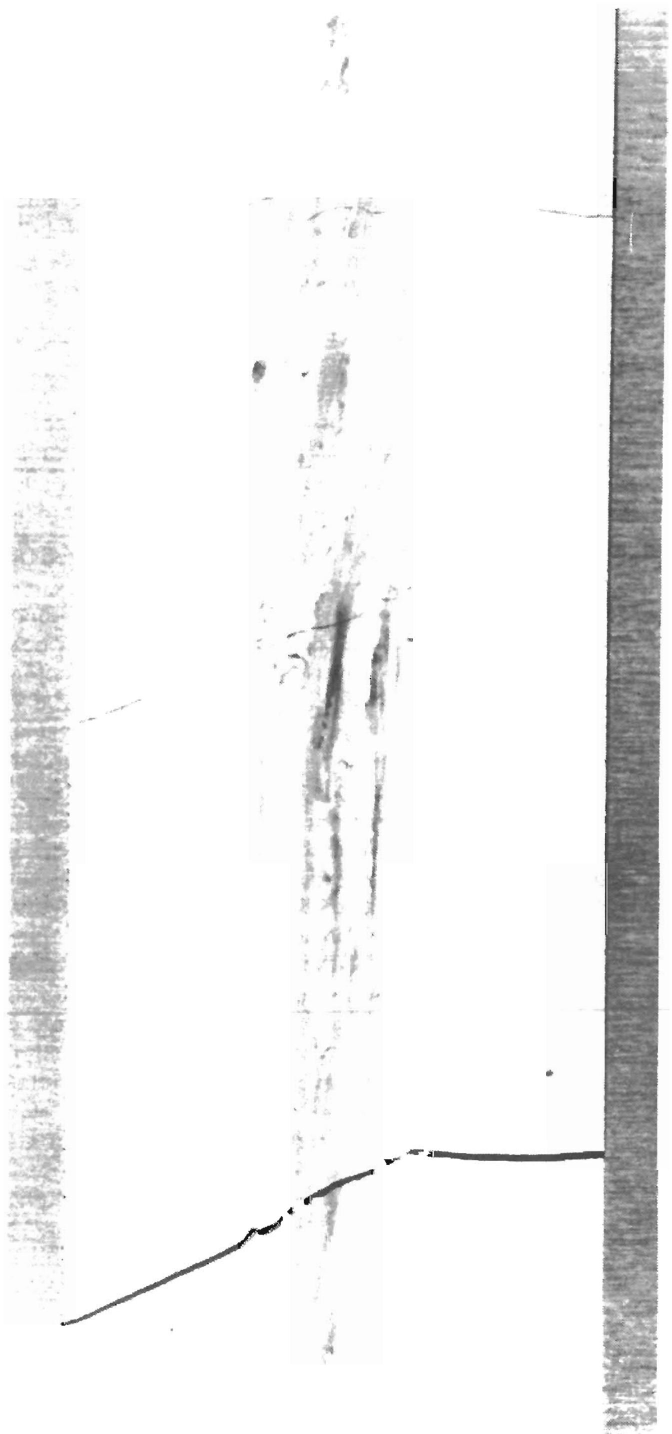

Figure 15.–Cross section of pull-test sample.

At point C (fig. 12), the maximum load-carrying capacity was reached; however, because of dilation of the sheared grout particles and confinement of the grout column, the frictional resistance and, consequently, the load, remained high between points C and D. This is referred to as residual load-carrying capacity. As displacement continued, the load transfer between the cable and the grout was caused by friction, and the interface of the grout began to smooth, as seen in the lower portion of the cutaway sample in figure 15. At point D, the load began to drop rapidly. The displacement that had occurred to this point was approximately 4.5 in. This characteristic of high residual loads at large magnitudes of displacement is an excellent attribute in many rock support situations because the supports will allow the rock to deform, thereby redistributing the loads to the surrounding rock.

The load-displacement behavior just described is quite typical for many of the pull-test samples tested. Major variations include the magnitude of the maximum load and the total length of displacement over which the residual load-carrying capacity remains high. Most samples reached the maximum load within the first 2 in of displacement and maintained a high load up to 4 in of displacement.

EMBEDMENT LENGTH VERSUS LOAD-DISPLACEMENT BEHAVIOR

Because rock joints are not spaced evenly, Bureau engineers were interested in what influence embedment length would have on the load-displacement behavior of the test samples. Consequently, 60 test samples were made (test series 2A and 2B, table 1), each containing a 0.625-in-diam cable embedded in a cement-based grout with a water-cement ratio of 0.45. The embedment lengths ranged between 8 and 30 in at increments of 2 in. Five test samples were made for each embedment length. As the grout mixer could not handle enough grout to fill all 60 samples, the samples were made in two batches. Test samples with embedment lengths from 8 to 20 in were taken from one batch (test series 2A) and samples with embedment lengths from 22 to 30 in were taken from the second (test series 2B). The samples were then tested randomly when they were 28 ± 1 days old (table 2).

The average load-displacement curve for each embedment length is shown in figure 16. Each of the 12 curves represents an average of five samples. It is obvious that the longer the embedment length, the greater the load-carrying capacity of the sample. The symbols representing each curve in figure 16 do not represent individual data points, but denote individual curves. Each curve is represented by approximately 600 data points. The maximum load-carrying capacity for each of the 60 samples tested was determined and plotted against embedment length (fig. 17). The data in figure 17 can be represented by the following first-order equation: $P = 5{,}537 + 1{,}244 \times L$. The data have a correlation coefficient of 0.98414.

The data were also fitted to a second-order equation; however, the correlation coefficients increased just slightly, to 0.98416, which is not sufficient to warrant the complication of using a higher order equation. The equation given above is only valid for embedment lengths between 8 and 30 in.

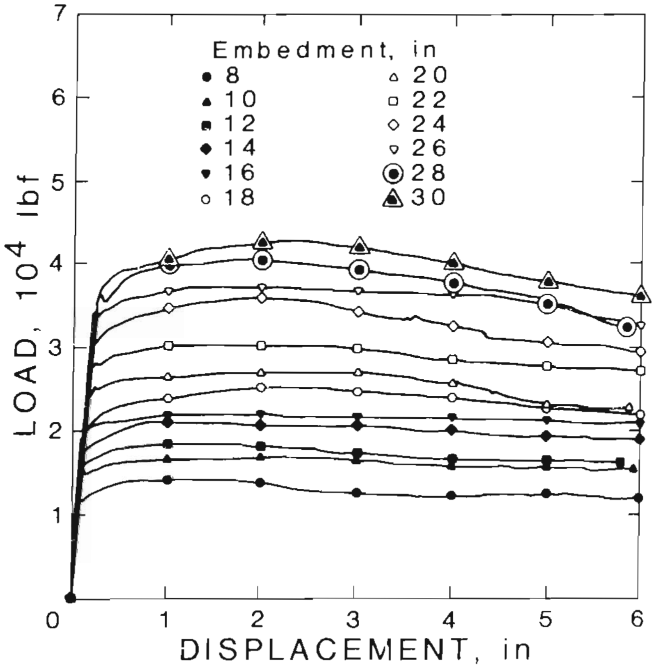

Figure 16.–Averaged 28-day load-displacement curves using different embedment lengths, test series 2A and 2B.

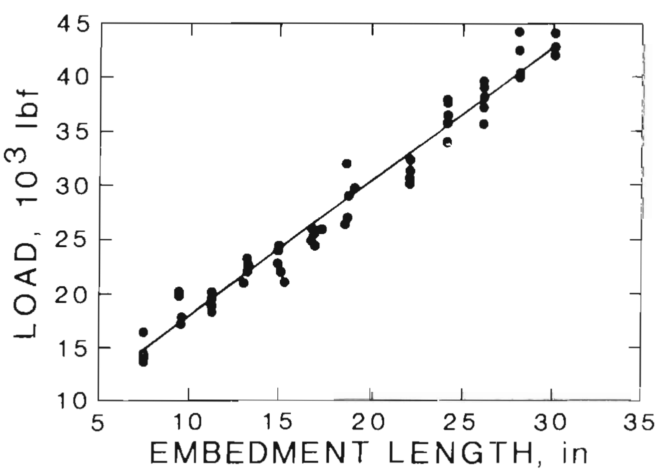

Figure 17.–Maximum load-carrying capacity versus embedment lengths, test series 2A, 2B, and 1.

BREATHER TUBES

The breather tube in a cable bolt support system plays an important role in the placement of the support because it allows air to escape from the hole. Overflow from the tube also indicates to the workers that the hole is filled with grout. When grouting is complete, the breather tube remains in the hole and becomes part of the support system.

The influence of the breather tube on the strength of cable bolt supports was investigated through test series 3A and 3B on 30 samples, each containing a cement grout with a water-cement ratio of 0.45, a single steel cable, and varying sizes of breather tubes filled with grout (table 1). An additional series of tests (test series 3C) was run on samples containing a cement grout with a water-cement ratio of 0.45, a single steel cable, and an unfilled 1/2-in-diam breather tube. The tests involving breather tubes were structured to address three basic questions:

1. Are the strength characteristics of the pull-test samples influenced by the size of the breather tube?
2. Does the presence of the breather tube influence the load-displacement behavior of the pull-test samples?
3. Does the presence of grout in the breather tube influence the load-displacement behavior of the pull-test samples?

To address these questions, tests were conducted using 1/4-, 3/8-, and 1/2-in-diam plastic breather tubes, which are the most common ones used with cable bolt supports. Based on the uncertainty of the load-displacement behavior of samples containing breather tubes and the potential for wide variations in test results, these tests were conducted twice (series 3A and 3B) to improve the statistical base. It was decided that as many samples should be made at the same time as possible using grout from the same batch and tested on the same day. This would reduce error caused by variations in grouts. However, testing five samples each for each of the three sizes at curing periods of 3, 7, and 28 days would total 45 samples for each test series, which was not realistic. Therefore, it was decided that for each of the two test series, five samples would be made for each size of breather tube and tested at 28 days, yielding 30 test samples. Each sample contained one cable, cement grout, and one breather tube filled with grout. The average 28-day test results are shown in table 2.

Test results for test series 3A and 3B were first analyzed to determine if there were significant variations between the results from each series. This was accomplished by conducting T-tests on the averaged maximum shear stress (pounds per square inch) for the samples for each size of tube The results are shown in table 3.

Table 3.–Statistical comparisons of similar tube sizes from test series 3A and 3B after 28 days of curing

Tube size and test series	Av. shear stress, psi	Statistical data,[1] T-value
1/4 in:		
3A	665	0.66
3B	676	
3/8 in:		
3A	650	.95
3B	691	
1/2 in:		
3A	648	1.17
3B	682	

[1]Z-value was ±1.86 for both test series.

Statistically, the corresponding sets of data for each of the three tube sizes can be considered to be from the same population because for each the T-value is within the range of the Z-value. This indicates there were no significant differences between the samples. Consequently, the two data sets from each tube size were combined, yielding three data sets instead of six (table 4).

Table 4.-Combined data for each breather tube size from test series 3A and 3B

Statistic	Tube size, in		
	1/4	3/8	1/2
Number of samples	10	10	10
Mean shear stress . . . psi . .	666	668	663
Standard deviation	50	63	43
Max. shear stress . . . . psi . .	750	752	739
Min. shear stress . . . . psi . .	604	582	602

To determine whether the strength characteristics of the pull-test samples were influenced by the size of the breather tube, an analysis-of-variance test was conducted on the results of pull tests conducted on the samples containing the three sizes of breather tubes. The F-ratio calculated was 0.16, which is very small compared with the critical value of 3.36 obtained from the F-tables in (*4*). This means that the three sets of pull-test data were from the same population and that the size of the breather tube did not influence the maximum shear stress of these samples.

The load-displacement relationship for the three sets of data (fig. 18*A*) also indicated that tube size did not influence the strength of the samples. The three curves approximate one another and the curve in test series 1 (no tube) very well. Consequently, the selection of the size of breather tube can be based on other factors, such as ease of use, availability, and cost, rather than on the influence of the size of breather tube on the strength of the support system.

The second question was, does the presence of a breather tube influence the shear strength of the pull-test samples? To answer this, all 30 of the samples from series 3A and 3B were combined and compared with the 28-day test results from test series 1 (table 5).

Table 5.-Comparison of data from test series 1, 3A and 3B combined, and 3C

Statistic	Test series		
	1	3A and 3B combined	3C
Number of samples	5	30	5
Mean shear stress . psi . .	668	666	593
Standard deviation	23	51	17
Max. shear stress . . . . psi . .	692	752	611
Min. shear stress . . . . psi . .	640	582	570

A T-test was conducted and the T-value of 0 was obtained compared to a Z-value of ±1.701. This means that the two sets of data were from the sample population and that the presence of the breather tube did not influence the maximum shear stress from this set of samples. The curves in figure 18*A* are extremely close, indicating that a breather tube filled with grout does not influence the strength of the pull-test samples.

One final evaluation of the test data was to compare data from the compression and tension tests for the grout used in these series. The average 28-day compressive stresses for samples from series 1 and combined series 3A and 3B were 6,940 and 7,187 psi, respectively. The average 28-day tensile stresses were 588 and 500 psi, respectively. The average compressive and tensile strengths for both sets of data were close, indicating that the grouts used were the same.

The third question was, does the presence of grout in the breather tube influence the behavior of the test samples? To address this question, pull-test samples (test series 3C) containing a cement grout with a water-cement ratio of 0.45, a single cable, and an empty 1/2-in-diam

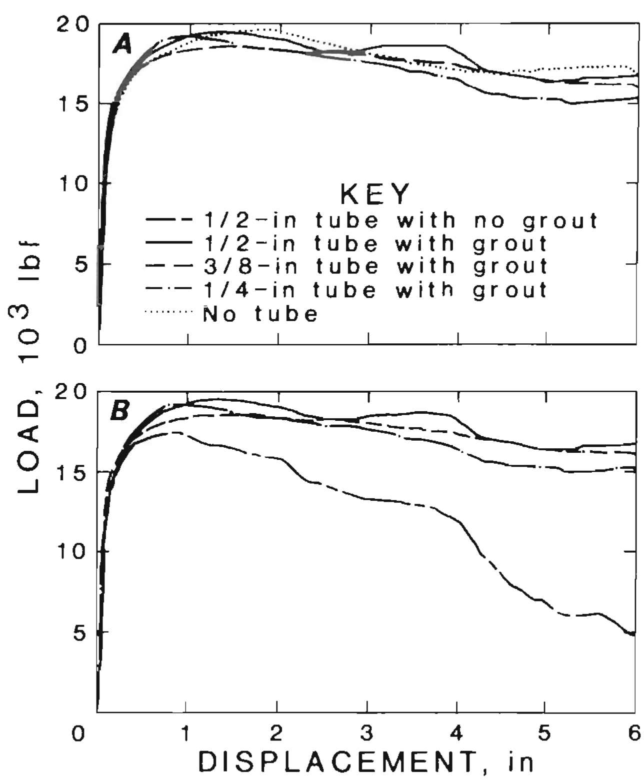

Figure 18.-Averaged 28-day load-displacement curves. ***A*, Tube size, test series 1, 3A, and 3B; *B*, with and without grout, test series 3A, 3B, and 3C.**

breather tube were made and tested. The average maximum 28-day shear stress for these samples was 593 psi. The test results were then compared with results from series 3A and 3B. The basic statistical data are shown in table 5.

A T-test was conducted on the sets of data and a T-value of 5.21 was obtained compared to a Z-value of ±1.658. The high T-value indicates that statistically, the two sets of data were not from the same population and that the absence of grout in the breather tube did have an adverse effect on the maximum strength obtained for these pull-test samples. Figure 18*B* shows averaged load-displacement curves for test series 3A, 3B, and 3C. These results appear reasonable because, as mentioned earlier, when the cable was pulled from the grout column, it could not rotate and began to shear the ridges of grout between individual wires. The fractured grout particles became compressed between the wires, causing additional resistance to movement. It was theorized that when this takes place in samples containing a breather tube filled with grout, the tube remains rigid and does not deform. However, if the tube is empty, it collapses easily, the grout particles are not compressed between the wires as much, and the resistance to pullout is decreased. The result is a reduction in maximum shear stress and a reduction in the residual load-carrying capacity of the system.

The presence of a breather tube in a cable bolt support system does not affect the load displacement of the system as long as the tube is filled with grout. In addition, the size of the breather tube does not influence the strength of the system. However, some caution should be exercised when using small-diameter tubes because they tend to plug easily, resulting in restrictions to the flow of air and grout out of the tube.

GROUTS

Water-Cement Ratios

Many of the mines installing cable bolt supports use a high water-cement-ratio grout so that pumping problems can be kept to a minimum. Unfortunately, large amounts of water reduce compressive and tensile strengths of the grout and increase water bleeding and cement particle sedimentation, which in turn reduce the total support length of the cable bolt. It is well established that lower water-cement ratios in concrete products produce higher strengths.

To determine the strength properties of grouts with different water-cement ratios, pull tests were conducted on samples containing single conventional cables and various water-cement ratios. Information collected by project personnel through literature surveys and visits to mining operations indicated that the mining industry uses water-cement ratios between 0.3 and 0.45 in grout. Consequently, this range of ratios was adopted for testing purposes.

Pull-test samples for test series 4 contained a single 0.625-in-diam cable. Grout for the first set of samples contained a water-cement ratio of 0.3. This grout was thick and would not flow through the funnel opening of the grout flow apparatus, nor would it flow into the hopper of the mono pump. However, pull tests conducted on support samples made from this grout and cured for 28 days showed an average maximum shear strength of 1,192 psi compared with 668 psi for samples made with a 0.45 water-cement-ratio grout (table 2); this is approximately a 78 pct increase in strength. In addition, grout bleeding and sedimentation were reduced from approximately 1.15 in/ft of embedment for samples with a water-cement ratio of 0.45 to 0.10 in/ft for samples with a water-cement ratio of 0.3. This increased the effective support length of each support (see section entitled "Grout Bleeding and Particle Sedimentation").

Additional pull tests on samples containing water-cement ratios of 0.35 and 0.40 showed average maximum shear strengths of 1,035 and 873 psi, respectively. Load-displacement curves for these samples, along with the curve for test series 1 (water-cement ratio of 0.45), are shown in figure 19.

Results from compression tests on grouts with various water-cement ratios are shown in table 2 and indicate a definite increase in compressive strength as the water-cement ratio decreases.

Bureau personnel made several trips to Canada to visit underground mines that use grouts with water-cement ratios of 0.3. The thick grout gives the grouting crews at these mines the option of either filling the cable bolt hole from the bottom up and using a breather tube, or filling it from the top down and not using a breather tube. The thick grout stays in the hole and does not run out. A

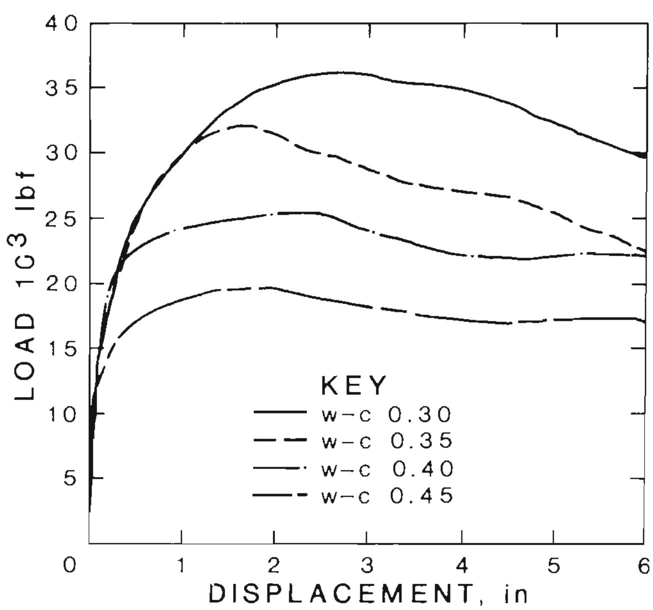

Figure 19.-Averaged 28-day load-displacement curves using different water-cement (w-c) ratios and no breather tubes, test series 4 and 1.

major advantage of using a low water-cement grout is improved quality control of the support system. If water is inadvertently added to a grout with a low-water content, then the resulting grout is likely still to have high strength and provide an effective support.

Based on laboratory test results and observations from various mines, low water-cement-ratio grouts offer the following advantages for cable bolt supports:

* High load-carrying capacities.
* High grout strengths.
* Less water bleeding and particle sedimentation.
* Greater flexibility in placing grout.
* Better quality control of grout.

Pumpability of Grouts

The primary disadvantage of low water-cement-ratio grouts is that they are more difficult to pump.

Pumpability of grouts refers to the ease or difficulty of pumping grouts given various conditions at a worksite. The ability to pump grout varies with such things as the type of cement used, water-cement ratio, use of sand, use of chemical additives such as water-reducing agents, type of pump, and distance the grout is pumped. An indication of the pumpability of a grout can be determined by measuring the time required for the pump to fill a given volume and the pumping pressure in the grout tube. The use of the grout flow test described below in "Physical Properties of Grouts" can also be used under some conditions, but this test is not as accurate as volume tests and grout tube pressure measurements.

To determine the pumpability of cement grouts with different water-cement ratios, various batches of grout were made using Type II portland cement. The batches were then pumped through a 50-ft-long, 0.75-in-ID hose using a pneumatic mono pump and an air line pressure of about 80 psi. Grout flow tests were run with a flow cone apparatus (fig. 11), grout tube pressure was measured with an on-line pressure gauge, and grout volume tests were run using a 0.25-ft^3 measuring bucket and monitoring the time required for the bucket to be filled. After each batch of grout was tested, a water-reducing agent was added (except batch 1) and the tests were again conducted. The agent used for the pumpability tests was obtained from Prokrete Industries,[3] Denver, CO, and is a modification of purified and desugared lignosulfonic acid.

Results of the pumping tests are shown in table 6. A grout with a water-cement ratio of 0.45 and no additives (batch 1 in table 6) was used as a baseline. This was the same grout used for most of the pull-test samples (table 1). As the water-cement ratio decreased, the grouts became more difficult to pump. Although the time required to pump 0.25 ft^3 only increased from 33 s for batch 1 to 38 s for batch 5 (grout in batch 7 would not flow into the pump hopper and could not be pumped), the groutline pressures increased from 22 to 60 psi. When a water-reducing agent was added to the mixes (batch 6), the time required to pump the specified volume decreased. In addition, both the hoseline pressure and grout flow time through the cone decreased. This indicated that the pumpability of the grouts had improved.

The volume tests were the best indication of improved grout pumpability. The grout flow test for batch 8 was stopped at 60 s with approximately 33 pct of the grout remaining in the cone; however, this grout was not difficult to pump even at a grout tubeline pressure of 67 psi.

These pumping tests give further support to the use of low water-cement ratio grouts because they show that these grouts can be pumped without difficulty.

[3]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

Table 6.–Results of grout pumping tests

Batch no.	W-C ratio, lb/lb	WRA-C ratio, lb/100 lb	Grout flow test, s	Rate per unit volume, s/0.25 ft^3	Grout tube line pressure, psi
1	0.45	No WRA	15.0	33.0	22
2	.40	No WRA	31.1	37.5	50
3	.40	0.25	15.0	30.0	20
4	.40	.40	12.8	30.4	5
5	.35	No WRA	51.6	38.8	60
6	.35	.40	16.0	31.0	35
7	.30	No WRA	(1)	(2)	(2)
8	.30	.50	>60.0	40.0	67

W-C Water-to-cement ratio.
WRA-C Water-reducing agent-to-cement ratio.
[1]Grout would not flow through cone.
[2]Grout would not flow into pump hopper.

Grout Bleeding and Particle Sedimentation

Water bleeding to the surface of the grout was first observed when pull-test samples for test series 1 were made. Bleeding is a process in which cement particles in the grout settle and water rises to the surface. It is expressed quantitatively as the degree of settlement in inches of grout per foot of grouted cable (*6*). This process begins immediately after grout is placed and continues until the grout has stiffened sufficiently so that sedimentation stops, usually after 2 to 4 h. At the time sedimentation stops, the top portion of the grouted cable will have a column of water surrounding it. The shear stress in this region is, of course, zero.

The degree of bleeding depends largely on the properties of the cement, such as fineness and chemical composition. It also depends on the ambient temperature and on the physical properties of any other material in the grout, such as sand or a steel cable. The seven-wire cable used in cable bolt supports actually increases bleeding because the tightly bundled wires allow water to pass through the bundle to the center, but block most of the cement particles (fig. 2). The cable then acts as a wick, and the water rises to the top of the grout column as the cement settles.

To determine the degree of bleeding in conventional cable bolt systems, two separate tests (A and B) were conducted. The first test involved single 0.625-in-diam cables grouted into five acrylic tubes of different lengths (1, 3, 6, 9, and 18 ft) with inside diameters of 2.25 in. The grout contained a water-cement ratio of 0.45. The second test involved five different lengths of doubled 0.625-in-diam cable grouted into the same diameter tubes with the same type of grout. In both tests, the amount of bleeding for each sample was monitored for 24 h after the tubes had been filled with grout. The results are shown in table 7. Figure 20 shows the rate at which bleeding took place for samples containing a single cable. Bleeding stopped at about 4 h, which is the approximate time the grout began to harden.

Table 7.-Results of grout bleeding tests

Cable type or grout	Tube length, ft				
	1	3	6	9	18
	TOTAL BLEEDING, in				
Single steel cable	1.10	3.62	7.20	11.02	20.51
Double steel cable . . .	.94	3.18	7.14	10.80	20.61
Epoxy-coated cable . .	.41	.83	1.22	.81	1.06
Thixotropic grout	.46	.47	.84	.91	1.80
	BLEEDING, in/ft				
Single steel cable	1.10	1.21	1.20	1.22	1.14
Double steel cable . . .	.94	1.06	1.19	1.20	1.14
Epoxy-coated cable . .	.41	.28	.20	.09	.06
Thixotropic grout	.36	.16	.14	.10	.10

The results from the single- and double-cable tests are very similar, indicating that a second cable in the hole does not increase bleeding. One possible explanation is that there is only a certain amount of bleeding that will take place for a given type of cement with a given water-cement ratio and the single cable provides a piping system sufficient to draw excess water to the surface, thereby allowing sedimentation to take place. If this is true, a second cable does not increase bleeding and sedimentation.

These results indicate that under the above-mentioned conditions, an average of 1.15 in of bleeding per 1 ft of cable can be expected. If it is assumed that this average is the same for longer grout columns, then for a 60-ft grouted hole, approximately 69 in (5.75 ft) of bleeding would occur, which means the top 9.6 pct of a 60-ft cable bolt would not support the rock.

Bleeding in a cable bolt support system does not necessarily constitute a hazard if the engineer designing the system is aware that this process occurs and, therefore, does not rely on a specific percentage of the upper part of the cable to support the rock. Bleeding does, however,

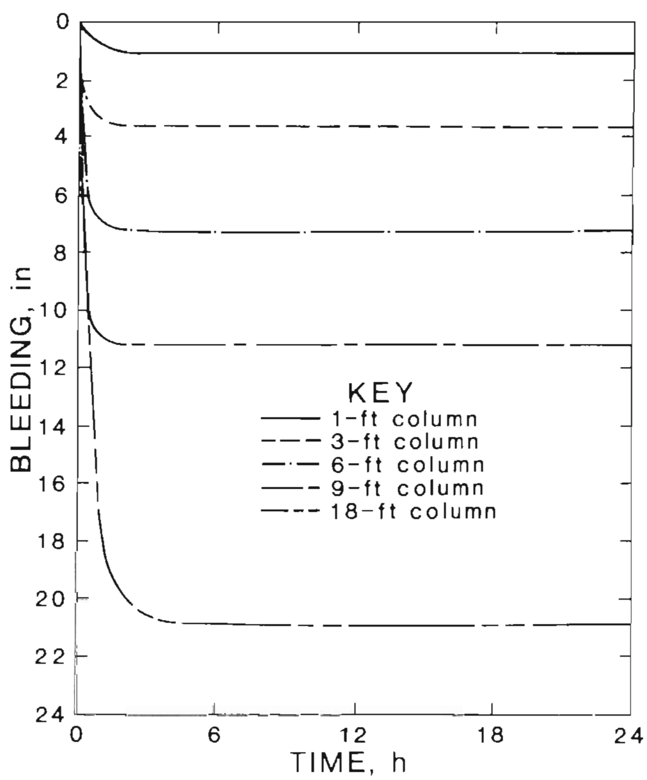

Figure 20.-Rate of grout bleeding for samples containing single cable.

increase mining costs and reduces productivity because of lost time and money involved in placing this part of the support system. Three practical methods to help minimize bleeding were briefly investigated under this project:

1. A coated cable to keep water from penetrating to the center of the cable.
2. Chemical admixtures to thicken the grout, thus keeping the cement particles in suspension without reducing the pumpability of the grout.
3. A grout with a low water-cement ratio (0.4 or less).

To determine the degree of bleeding associated with coated cables and thick grouts (thixotropic), two additional large-scale tests were conducted using the same number and size of acrylic tubes as used in tests 1 and 2. Test 3 involved conventional 0.625-in-diam cables that had been coated with epoxy by the manufacturer. These coated cables were marketed for use in prestressed concrete members to provide corrosion resistance (7). The cable also had silica grit embedded in the epoxy to increase the resistance of the cable to pullout. The various lengths of cable were embedded in acrylic tubes with a cement grout containing a water-cement ratio of 0.45. Test 4 involved single, bare cables that also had been embedded in acrylic tubes; however, the grout contained an antibleed chemical admixture at 1.2 pct by weight of cement. The admixture is a blend of organic polymers that act as dispersants to keep the cement particles well distributed throughout the mix and as a thixotropic agent that makes the grout stiff to reduce bleeding, but that allows the grout to become liquid when agitated.

The results from bleeding tests 3 and 4 are shown in table 7. It is obvious that the degree of bleeding has been reduced considerably using both the coated cable and thixotropic grout. For example, with the 18-ft-long cables, bleeding was reduced from 20.51 in using a single, bare cable to 1.06 and 1.80 in for the coated cable and thixotropic grouts, respectively. For the coated cable, bleeding was reduced because the water was not able to penetrate the individual wires of the cable; for the thixotropic grout, the additive in the grout acted as a dispersant, keeping the cement particles in suspension and not allowing the water to separate out and penetrate between the wires of the cable.

Large-scale bleeding tests were not conducted on grouts containing water-cement ratios of 0.4 or less because of the number of different grouts involved and the time required to conduct each test. However, the 45 pull-test samples made to determine the load-displacement behavior of cable bolt samples with different water-cement ratios (test series 4) were monitored closely during the first 24 h of curing, and grout settlement was measured after this period. Results show an average of 0.19, 0.39, and 0.76 in/ft of sedimentation for grouts containing water-cement ratios of 0.3, 0.35, and 0.4, respectively. These values, compared with average values of 1.15 in/ft for grouts using a water-cement ratio of 0.45, indicate that lower water-cement ratios can significantly reduce bleeding and grout sedimentation.

Determining which of the above-mentioned methods for reducing bleeding is best will depend on conditions at individual mines. Lower water-cement ratios not only reduce bleeding, but increase pull-out strength (table 2), and although these grouts are more difficult to pump with mono-type pumps, a water-reducing agent can be useful. The admixture used in the thixotropic grout adds approximately \$.07/ft to the cost of the support system, but does not require a change in pumps. The epoxy-coated cable costs approximately \$.50/ft more compared with conventional bare cables. However, epoxy-coated cable with embedded grit increased the shear stress of the pull-test samples by approximately 31 pct over bare cable (test data on these cables will be covered under Part 2). This added strength could lead to a reduction in the number of grouted cables required per unit area of rock being supported.

High Curing Temperature

The strength of the grout in cable bolt supports is dependent on many factors, an important one being the temperature at which the grout has been cured. To get an indication of what effect high rock temperatures might have on cable bolt supports, pull-test samples in test series 5 were cured at 127° F, which is the approximate temperature at the 7,500-ft level of the Homestake Mine. The samples were made in the same manner as those for test series 1 except that they were cured in a large oven. The only difficulty was that the compression and tension samples were not properly sealed and rapid evaporation of moisture caused excessive shrinkage cracks. Consequently, these samples were not tested.

The average shear stress for test series 5 samples at 28 days was 791 psi compared with 668 psi for test series 1 samples cured at 70° F (table 2), an increase of approximately 18 pct. The higher temperature helped to speed up the chemical reaction in the cement hydration process, thus giving the grout higher strengths at an earlier age. Because the grout was sealed within the pipe assembly, evaporation of the free water in the cement was reduced, thereby assuring that hydration could take place to completion. Figure 21 shows a plot of average maximum shear strength versus curing time for samples from test series 5 and 1.

Sand-Cement Grout

Test series 6A, 6B, and 6C involved the study of sand-cement grouts compared with grouts in which just cement and water had been used. The grouts in this series were made of 1.4 parts of sand to 1.0 part of cement by weight and had a water-cement ratio of 0.45. The sand used was a crushed aggregate that had a specific gravity of 2.58 and a moisture absorption value of 1.97 pct. Particle distribution is shown in table 8.

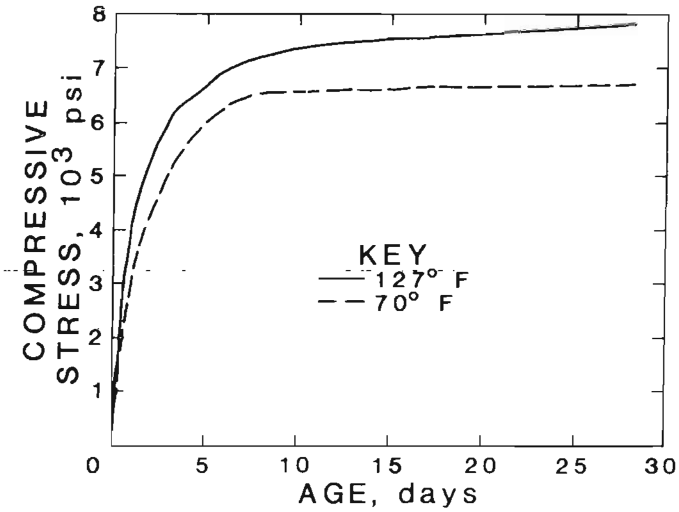

Figure 21.–Average shear strength versus curing time, test series 5 and 1.

Table 8.–Analysis of fine aggregate used in sand-cement grout, percent passing sieve

Sieve size	Received	Recombined	ASTM Standards
8	53.4	90.0	80-100
16	30.1	67.5	50-85
30	15.1	42.5	25-60
50	9.1	20.0	10-30
100	6.5	6.0	2-10

Since the aggregate in table 8 did not meet ASTM standards for a concrete fine aggregate, it was mechanically separated and then recombined to meet these standards. The recombined aggregate had a fineness modulus of 2.74. ASTM specifications for fine aggregate in concrete require a fineness modulus of not less than 2.3 or more than 3.1.

The addition of sand to the grout greatly improved shear stress along the cable-grout interface. The average 28-day maximum shear stress for test series 6A samples was 900 psi compared with 668 psi for test series 1 samples, which is a 35 pct increase. This is significant in that the cement content of the grout was reduced from 100 pct solids (test series 1) to 42 pct (test series 6A). The sand that made up the remaining 58 pct is, in general, much cheaper than the cement it replaced.

The interlocking of sand particles around the cable strand is felt to be a major contributor to the increased shear stress. In addition, the increased tensile stress (table 2) helps reduce microscopic cracking in the grout.

The grout in test series 6A was very stiff and would not flow through the flow cone, nor could it be pumped with a mono pump. Also, there was some segregation of sand particles from the cement matrix when the grout was allowed to set for just a few minutes. To overcome stiffness and segregation problems, a water-reducing agent was added to the grout in test series 6B. The purpose of using such a water-reducing agent with the sand-cement grout was not to decrease the water content of the grout mix, but to improve the pumpability of the grout when using the same amount of water.

The grout in test series 6B contained the same sand-cement and water-cement ratios as test series 6A, except 0.25 lb of water-reducing agent was added to each 100 lb of cement in test series 6B. The agent helped reduce the viscosity of the grout; however, the grout flowed slowly through the flow cone (table 2) and could not be pumped with a mono pump. Consequently, a third batch of sand-cement grout (test series 6C) was made with a water-reducing agent at a ratio of 0.45 lb per 100 lb of cement. This grout did not flow much better through the flow cone (table 2), but it could be pumped with the mono pump. However, this was not done because of possible wear on the rubber liner of the screw feed shaft. The grout in test series 6C was easy to mix and the sand particles did not segregate from the cement matrix.

Statistical data on pull-test samples from the three test series are shown in table 9. The mean shear stresses and standard deviations for the series are very similar, indicating that addition of a water-reducing agent in the grout did not alter the strength of these samples. Further verification was obtained by conducting an analysis-of-variance test on the three sets of data. The results show a F-ratio of 0.44 compared with a critical value of ±3.89 from a F-table (*3*), thereby indicating that the three sets of data were from the same population. Figure 22 shows averaged load-displacement curves for 28-day pull-test samples from test series 1 and 6C.

Table 9.–Results from test series 6A, 6B, and 6C

Statistic	Test series		
	6A	6B	6C
Number of samples	5	5	5
Mean shear stress ... psi ..	900	896	865
Standard deviation	71	61	63
Max. shear stress .... psi ..	1,012	976	942
Min. shear stress .... psi ..	838	812	789

Physical Properties of Grouts

Test results for compressive and tensile strengths are shown in table 2. Table 10 shows the values for Young's modulus for a neat cement grout with a water-cement ratio of 0.45 and a sand-cement grout with a water-cement ratio of 0.45. Figure 23 shows a typical curve of lateral and longitudinal strains for a neat cement grout sample. As mentioned before, compressive and tensile strength tests, as well as tests for Young's modulus, were conducted on the various grouts.

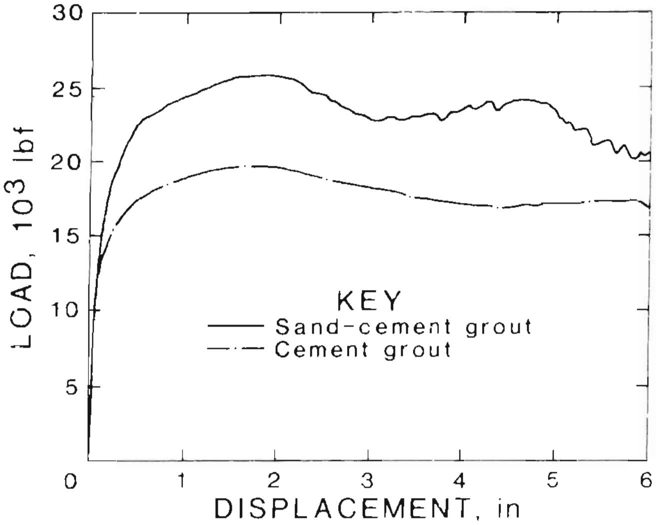

Figure 22.-Averaged 28-day load-displacement curves using different grouts, test series 1 and 6C.

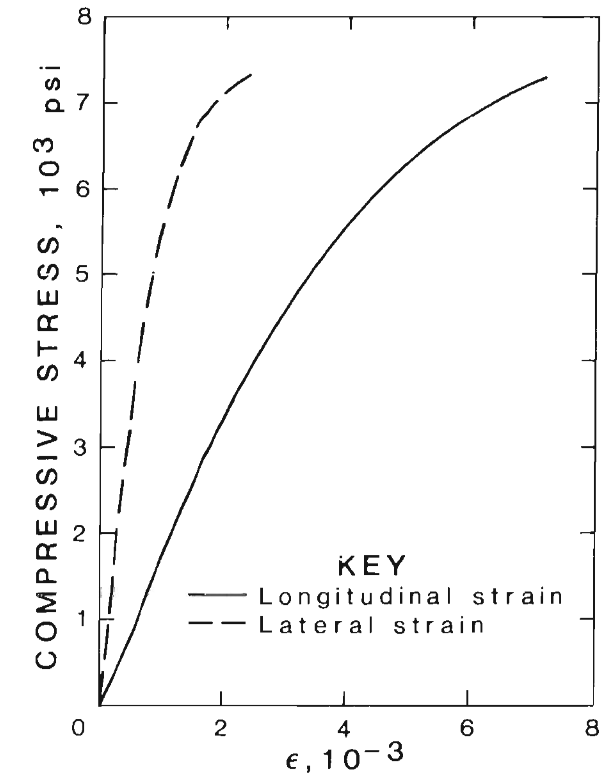

Figure 23.-Typical stress-strain curves for lateral and longitudinal strain for a cement grout.

Table 10.-Young's modulus for cement and sand-cement grouts

Sample No.	Cement modulus, 10^6 psi	Sand-cement modulus, 10^6 psi
1	1.925	3.061
2	1.941	2.972
3	1.765	2.970
4	1.681	2.956
5	1.677	2.888
6	1.675	NT
7	1.674	NT
8	1.654	NT
9	1.627	NT
Av	1.735	2.969

NT Not tested.

DOUBLE CABLES

Test series 7 and 8 were conducted to determine what influence double cables would have on the load-displacement behavior of these supports. By adding a second cable, the surface contact area between the cables and the grout is doubled compared with a single cable. Therefore, one would expect to obtain at least a 100 pct increase in the load-carrying capacity of the system for an identical length of embedment.

Double Cables Without Breather Tubes

A preliminary series of samples was made using 12-in embedment lengths. Results showed an average maximum load-carrying capacity of approximately 50,000 lbf after 7 days of curing. It was estimated that 28-day strengths would exceed 60,000 lbf, and there was some concern about the safety of the testing apparatus. Consequently, the embedment length of the double cable samples was reduced from 12 to 10 in. Test series 7 samples were then made using two 0.625-in-diam cables and a grout with a water-cement ratio of 0.45. Test results (table 2) show an average maximum load-carrying capacity after 28 days of curing of 41,080 lbf for the pull-test samples. The average embedment length of the samples was 9.36 in after the grout had cured. This embedment length and average maximum load equates to an average shear strength of 838 psi [$41,080/(9.36 \times 2 \times 2.62) = 838$].

The average maximum loads obtained from tests on single and double cable samples cannot be compared directly because the lengths of the test samples varied. However, average maximum shear stress can be compared because such stresses represent the maximum load per unit area. Results in table 11 show an average shear stress of 838 psi for double cable samples compared with 668 psi for single cables, which is an increase of approximately 25 pct. This is important because it is more economical to place two cables in a single hole and gain more than twice the strength than to drill extra holes.

Table 11.-Results from test series 1, 7, and 8

Statistic	Test series		
	1	7	8
Number of samples	5	5	5
Mean max. load . . . . . lbf . .	[1]19,820	[2]41,080	[3]43,058
Mean shear stress . . . psi . .	668	838	881
Standard deviation	23	121	111
Max. shear stress . . . . psi . .	692	1,019	995
Min. shear stress . . . . psi . .	640	738	750

[1]Based on 11.3 in of embedment.
[2]Based on 9.36 in of embedment.
[3]Based on 9.33 in of embedment.

The load-displacement curves for double cables are shown in figure 24*A*. These curves indicate that the average maximum loads for double cable samples were achieved at shorter displacement lengths compared with single cables (fig. 12). Consequently, double cable supports appear to be stiffer than single cable supports and may not allow the degree of rock movement that single cable supports do.

Double Cables With Breather Tubes

Breather tubes are also used in upholes involving double cables. Test series 8 was conducted to determine the influence of a breather tube on the support behavior of double cables. The samples in this series contained a cement grout with a water-cement ratio of 0.45, two 0.625-in-diam cables, and one 0.5-in-diam breather tube filled with grout. The results of the pull tests were then compared with results from test series 7 (table 11).

Initially, it appeared that the presence of a breather tube in series 8 samples increased the overall strength characteristics of double cable samples because the mean shear stress increased from an average of 838 psi in series 7 to an average of 881 psi in series 8. However, from a statistical standpoint, the samples from these two series were from the same population. This was determined by conducting a T-test on the 28-day shear strengths obtained from the pull-test samples. The T-value obtained was -0.59 compared to a Z-value of ± 1.860. This is well within the limits of the Z-value and indicates that the two sets of data were from the same population and that the presence of the breather tube did not influence the maximum shear strength obtained from these samples.

The load-displacement relationship, shown in figure 24*B*, for these two sets of data also indicated that the presence of a breather tube in series 8 did not influence the behavior of the double cable samples. The two curves are very similar in shape and magnitude. This behavior was not surprising since the presence of the breather tube in the single cable samples did not influence the performance of the samples. It was concluded that if the breather tubes are filled with grout, then their presence will not influence the performance of either single or double cable systems.

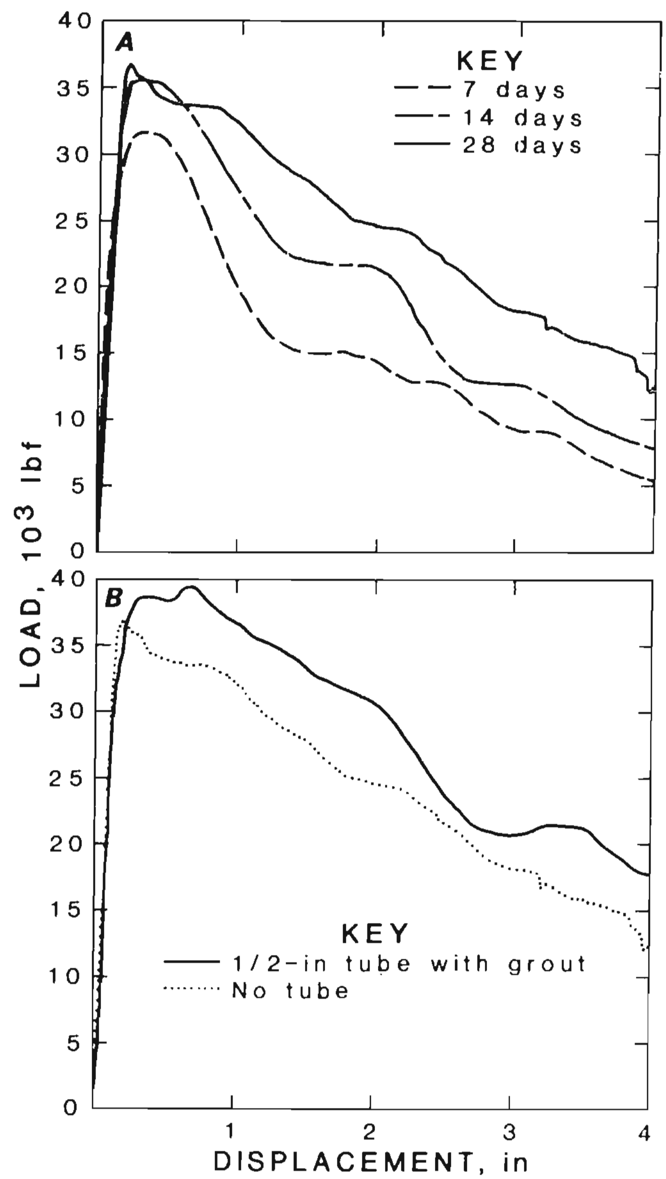

Figure 24.-Load-displacement curves using double cables. *A*, Averaged displacement at 7, 14, and 28 days, test series 7; *B*, with and without breather tubes at 28 days, test series 7 and 8.

CONCLUSIONS

Laboratory test results showed that cable bolt pull-test samples containing a single cable develop average shear strengths of approximately 668 psi after 28 days of curing and maintain very high residual load-carrying capacities during testing. The results also showed that the maximum load-carrying capacity of these cable bolt samples increased linearly as embedment length increased for lengths between 8 and 32 in. In addition, the following components and conditions were shown to increase the average shear strength of pull-test samples:

* The presence of two cables.
* Low water-cement ratios.
* High curing temperatures.
* Sand-cement grout.

Based on laboratory data, the use of two cables in a single hole is beneficial because the load-carrying capacity is more than twice that of single cables. However, test data showed that maximum loads for double cable samples were achieved at shorter displacement lengths compared with single cables, indicating that double cable supports are stiffer than single cable supports because they allow less rock movement. Laboratory data also indicate that it is beneficial to use low water-cement-ratio grouts in cable bolt supports to provide higher shear strengths and improve the quality control of the grout. The low water-cement-ratio grouts also reduce water bleeding, thereby increasing the effective length of the cable bolt support. The problem of pumping low water-cement-ratio grouts can be overcome by using a chemical admixture that improves pumpability. The use of sand-cement grout also increased the shear strength of cable bolt pull-test samples; however, the use of this grout would require the use of a pump that can handle sand particles.

Grout-filled breather tubes did not influence the shear strength of the cable bolt pull-test samples provided they were filled with grout. Neither did the size of the breather tube (1/2, 3/8, or 1/4 in diam) influence the strength of the cable bolt samples.

The laboratory evaluation of cable bolt supports shows that it is important for ground control engineers to recognize and understand the impact that each component of a cable bolt support has on a system and to incorporate beneficial properties into a support system whenever possible.

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